Up-Sampling (5B)

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11/9/12

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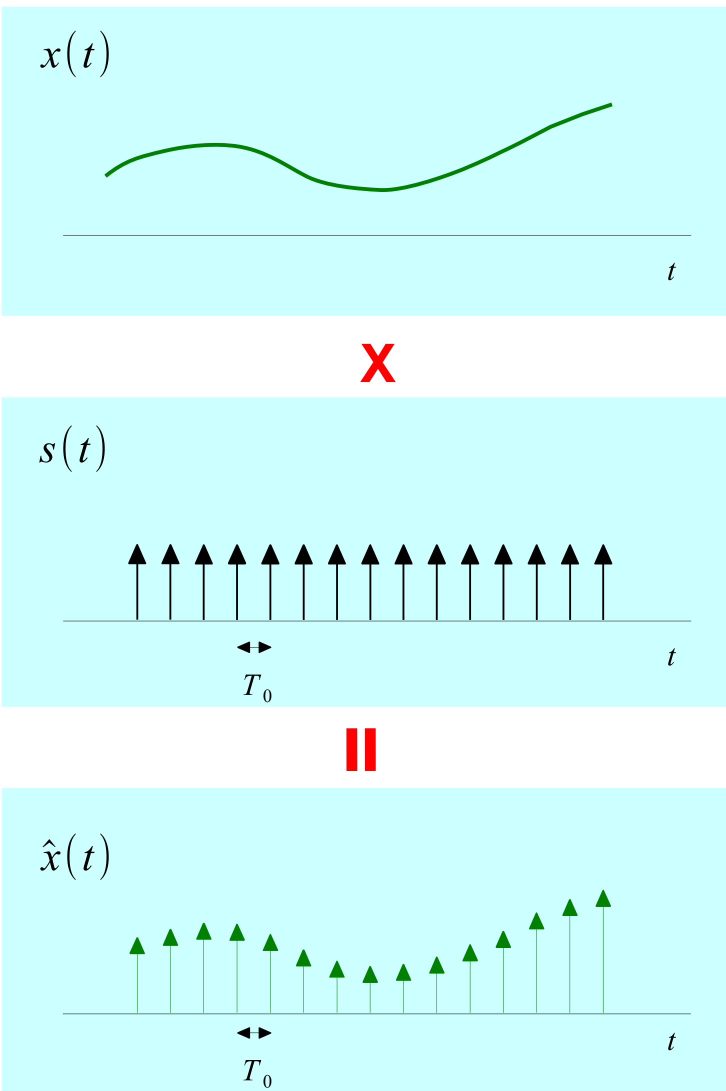
Spectrum Replication (1)

Ideal Sampling



$$\hat{x}(t) = \sum_{n=-\infty}^{+\infty} x(nT_0)\,\delta(t-nT_0)$$

$$s(t) = \sum_{n=-\infty}^{+\infty} \delta(t-nT_0)$$

$$= \frac{1}{T_0}\sum_{m=-\infty}^{+\infty} e^{+j2\pi m f_s t}$$

$$\hat{x}(t) = \frac{1}{T_0}\sum_{n=-\infty}^{+\infty} x(t)\, e^{+j2\pi m f_s t}$$

Shift Property

$$\hat{X}(f) = \frac{1}{T_0}\sum_{n=-\infty}^{+\infty} X(f - m f_s)$$

Spectrum Replication (2)

$$S(f) = \frac{1}{T}\sum_{m=-\infty}^{+\infty} \delta(f - m f_s)$$

Convolution in Frequency

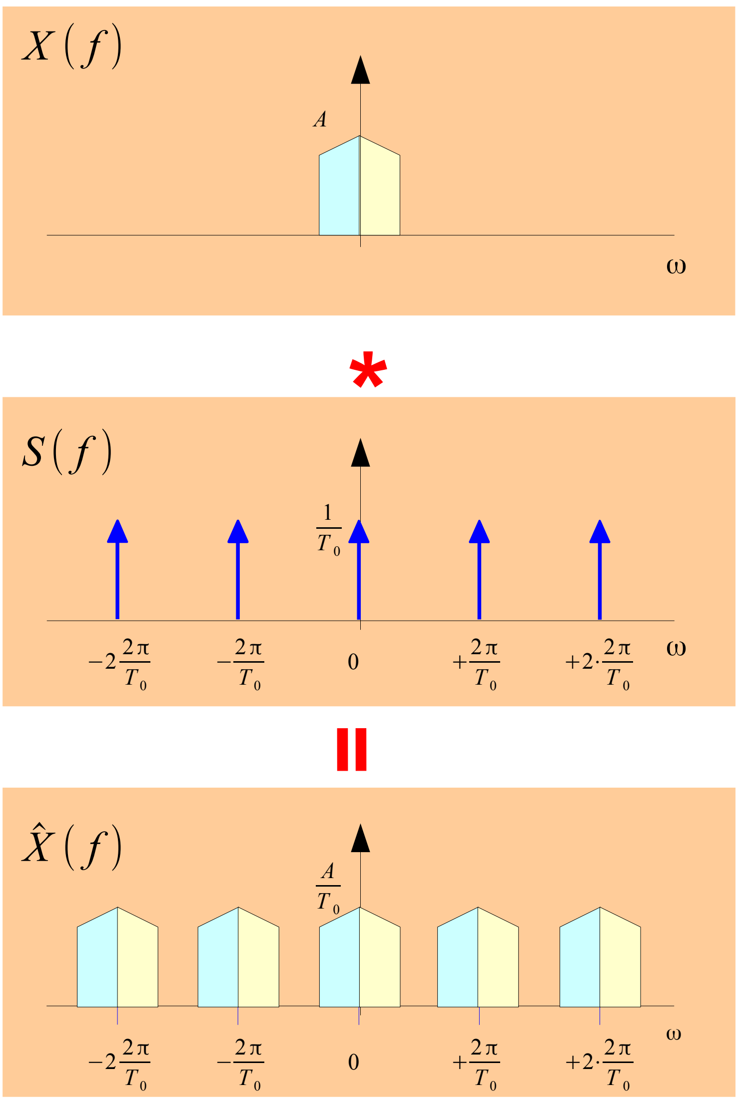
$$\hat{X}(f) = X(f) * S(f)$$

$$= \int_{-\infty}^{+\infty} X(f-f')S(f')\,df'$$

$$= \frac{1}{T_0}\sum_{m=-\infty}^{+\infty}\int_{-\infty}^{+\infty} X(f-f')\delta(f'-m f_s)\,df'$$

$$\hat{X}(f) = \frac{1}{T_0}\sum_{n=-\infty}^{+\infty} X(f - m f_s)$$

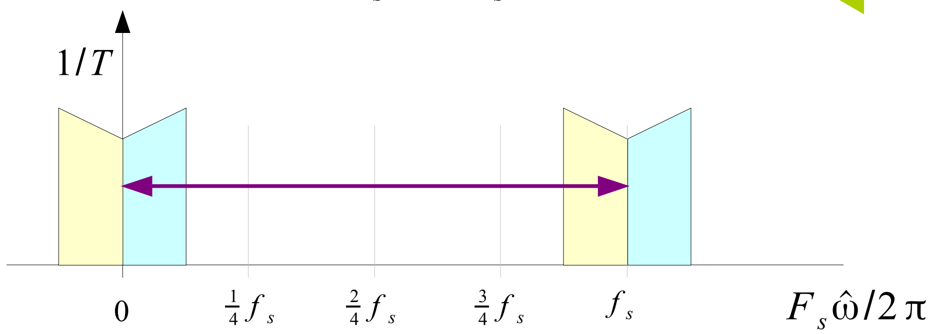
Frequency Domain



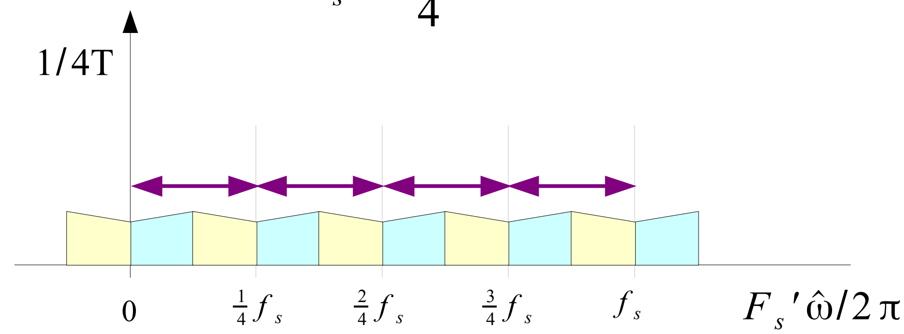
Increasing Sampling Frequency

UP

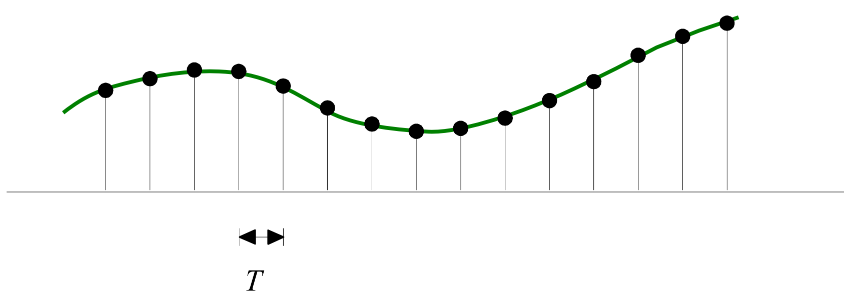
$F_s' = f_s$

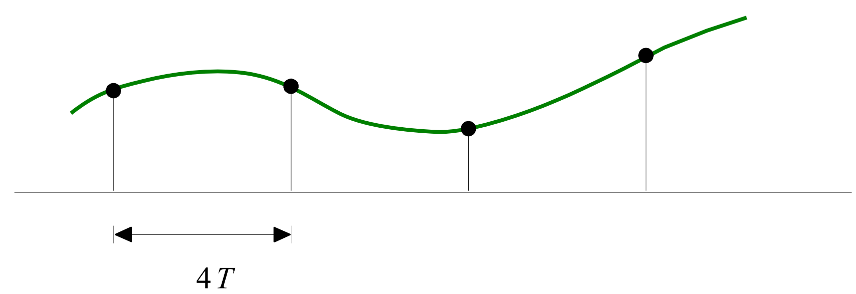


$F_s = \frac{f_s}{4}$

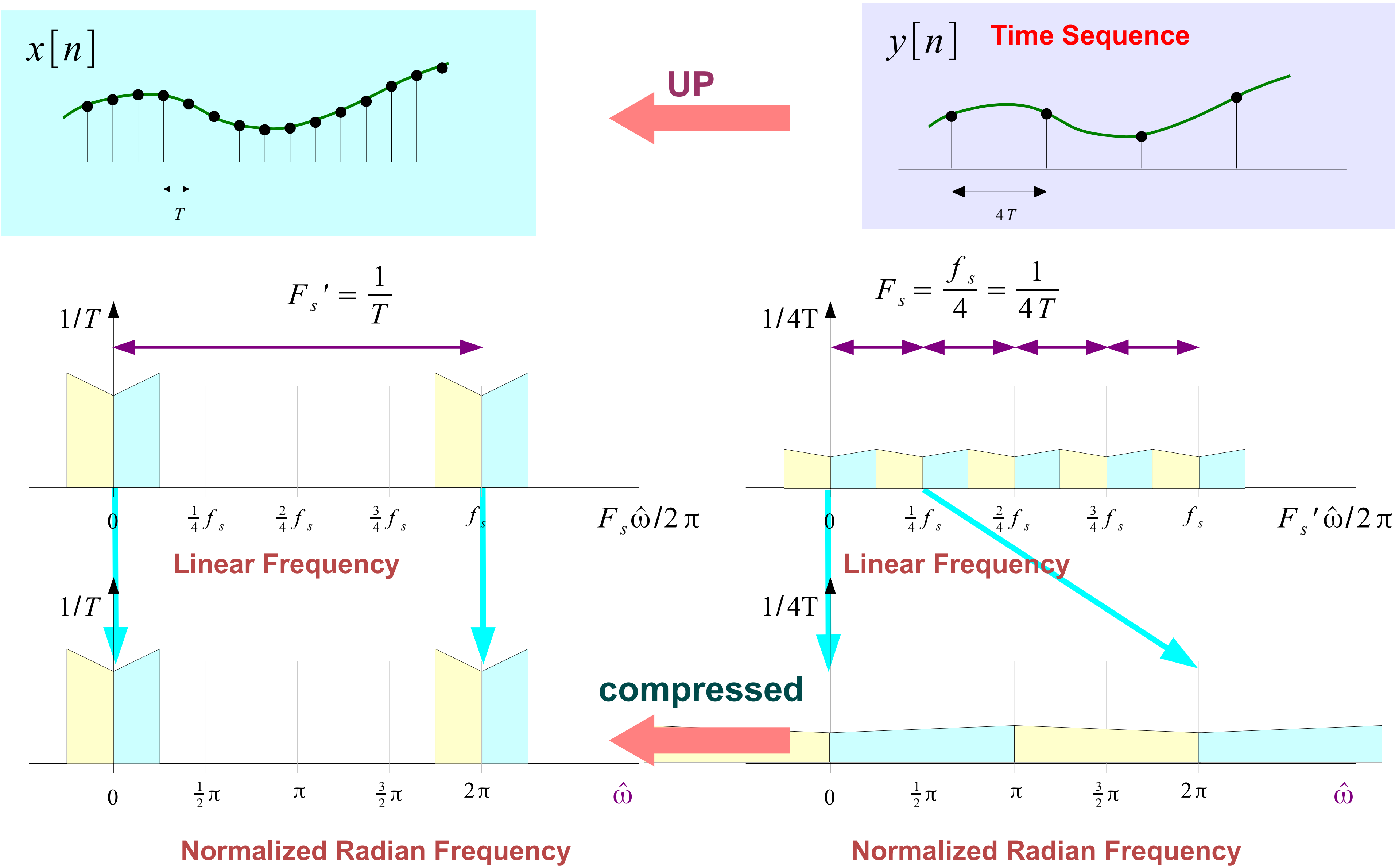


Sampling Frequency	$F_s' = f_s$	Sampling Frequency	$F_s = \frac{f_s}{4}$
Sampling Time	$T' = \frac{T}{4}$	Sampling Time	$T = \frac{4}{f_s}$



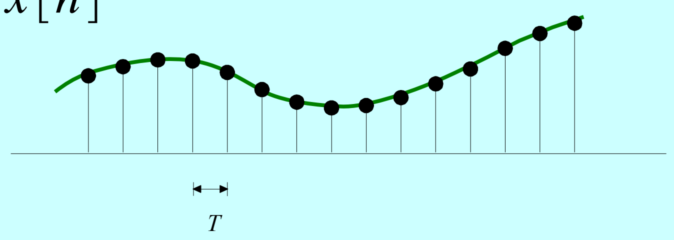


Fine Sequence & Spectrum



Normalized Radian Frequency

$x[n]$



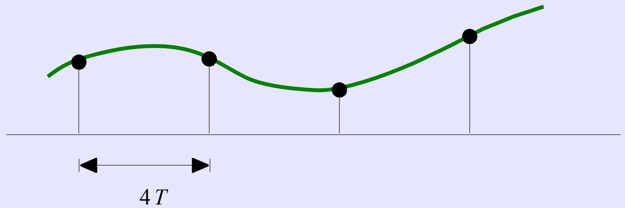
$$\hat{\omega} = \omega \cdot T_s = \frac{\omega}{1/T_s}$$

$$\hat{\omega} = \frac{\omega}{f_s} = 2\pi \frac{f}{f_s}$$

Normalized to f_s

Normalized Radian Frequency

$y[n]$ **Time Sequence** f_B



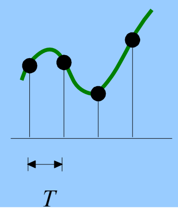
$$\frac{f}{f_s} = \frac{f_B}{1/4T} = f_B \cdot 4T$$

The Same

- **Time Sequence**
- **Normalized Radian Frequency**

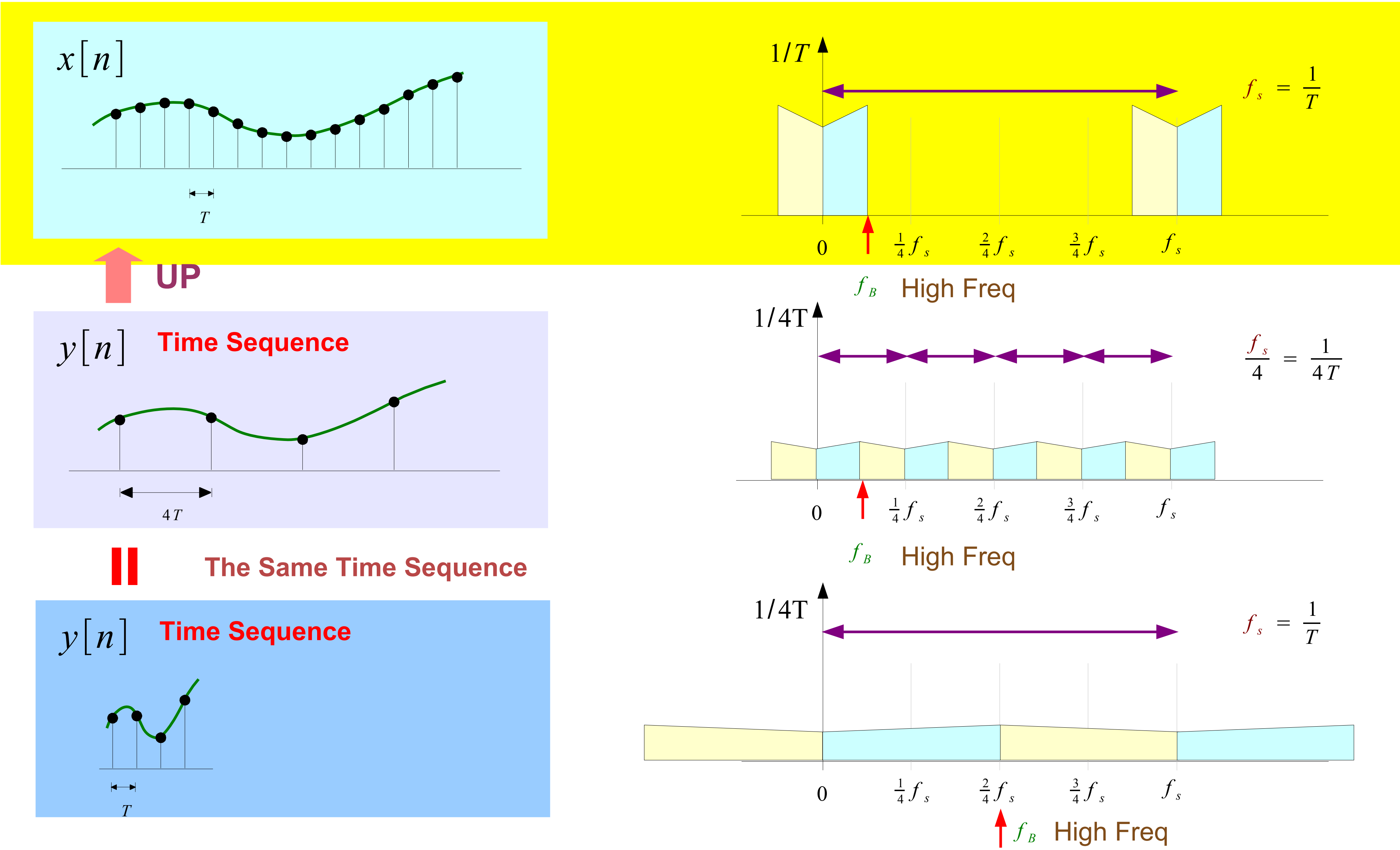
$$\frac{f}{f_s} = \frac{4 f_B}{1/T} = f_B \cdot 4T$$

$y'[n]$ **Time Sequence** $4 f_B$

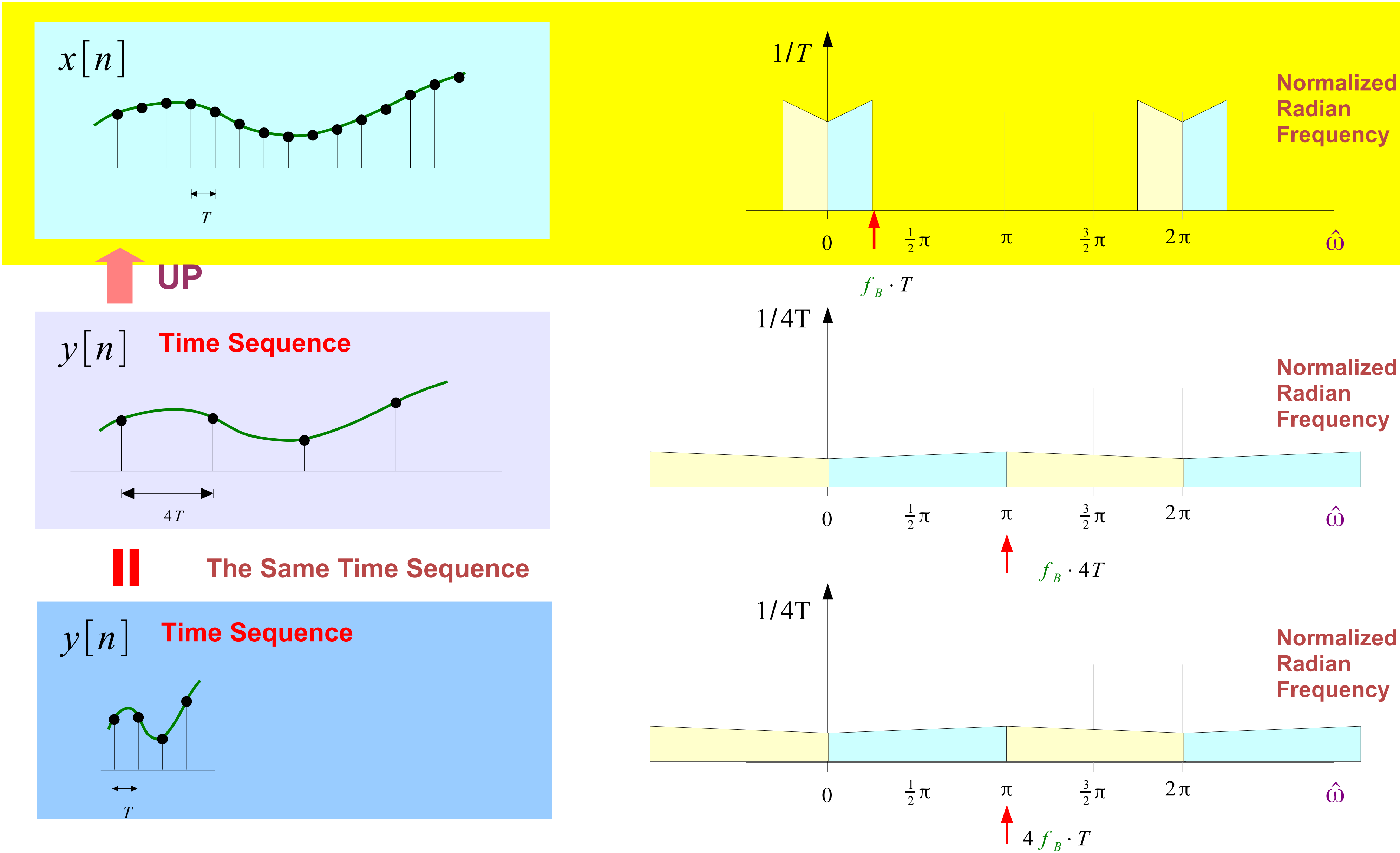


The Highest Frequency:

Fine Sequence Spectrum – Linear Frequency

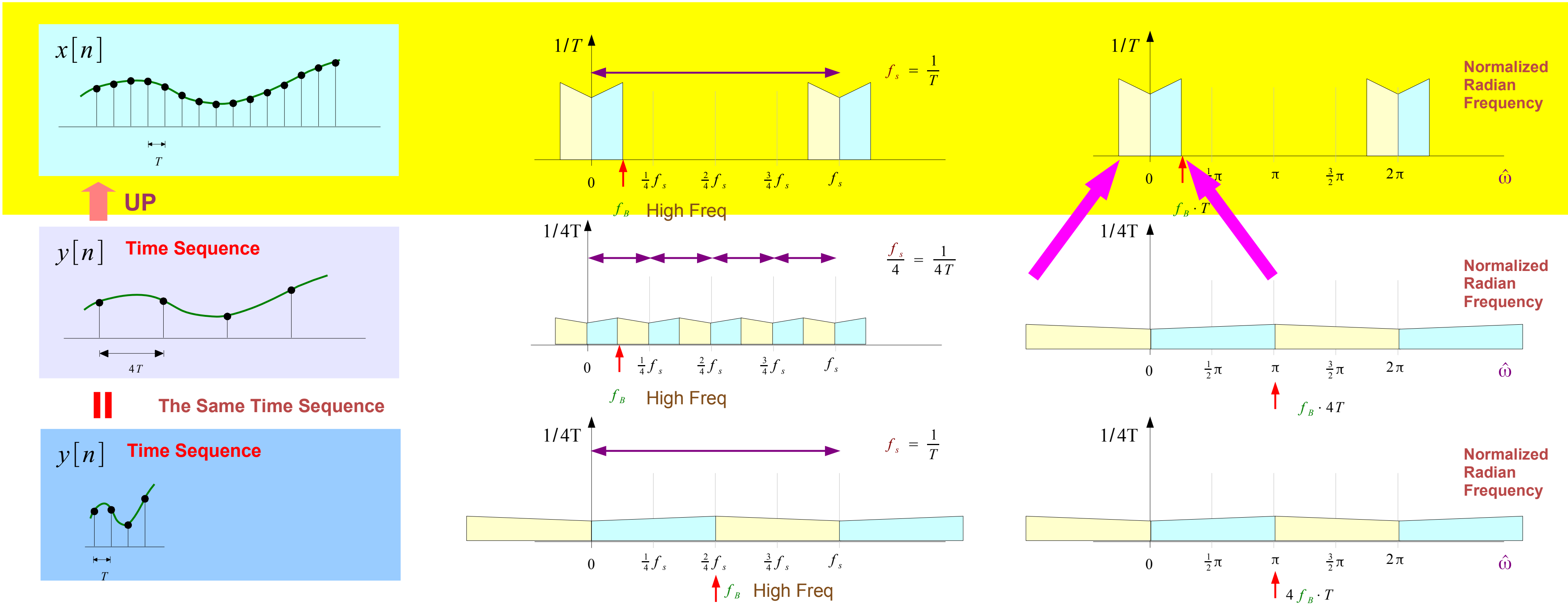


Fine Sequence Spectrum – Normalized Frequency



Fine Sequence Spectrum – Linear Frequency

Linear Frequency **Normalized Radian Frequency**

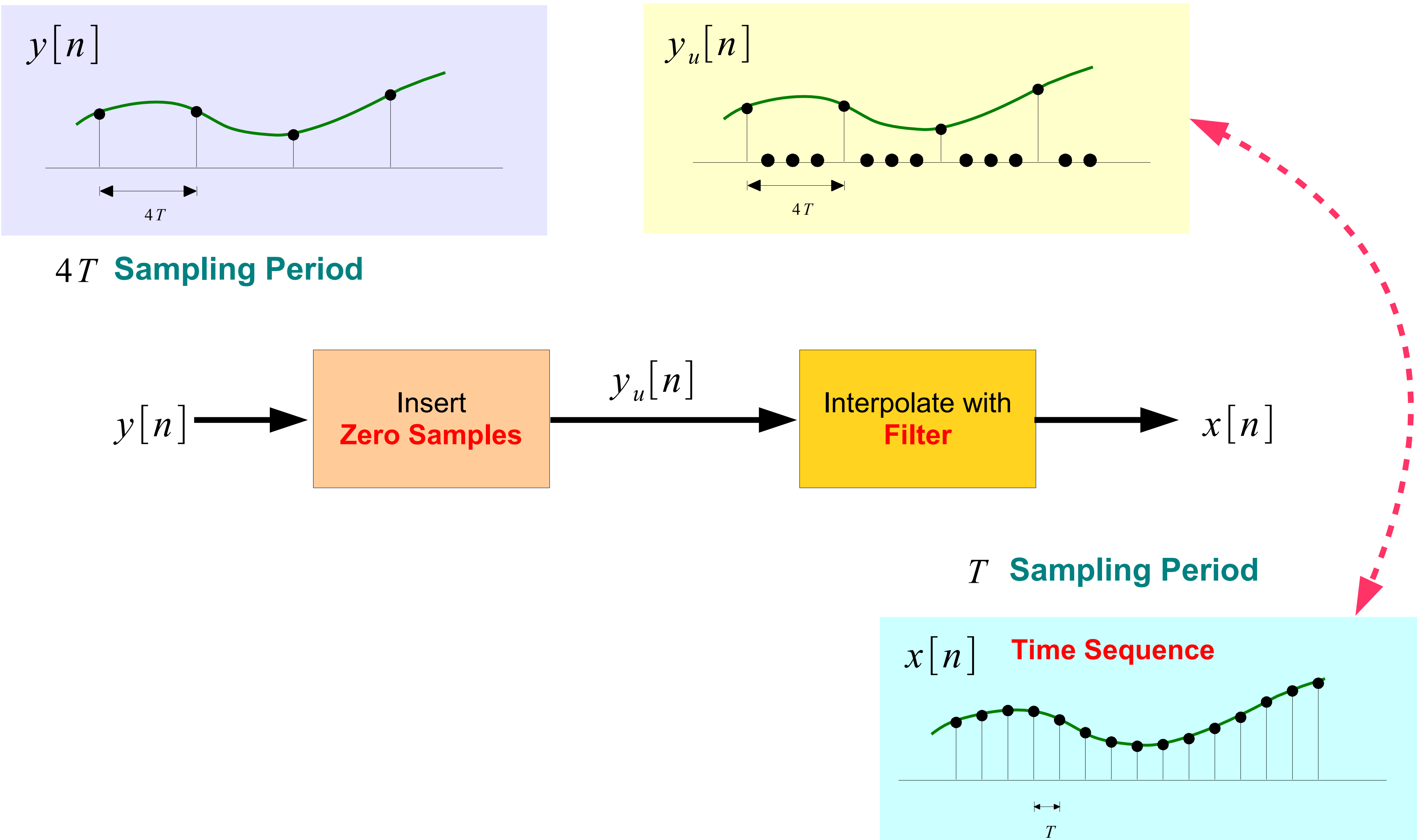


Fine Sequence Spectrum

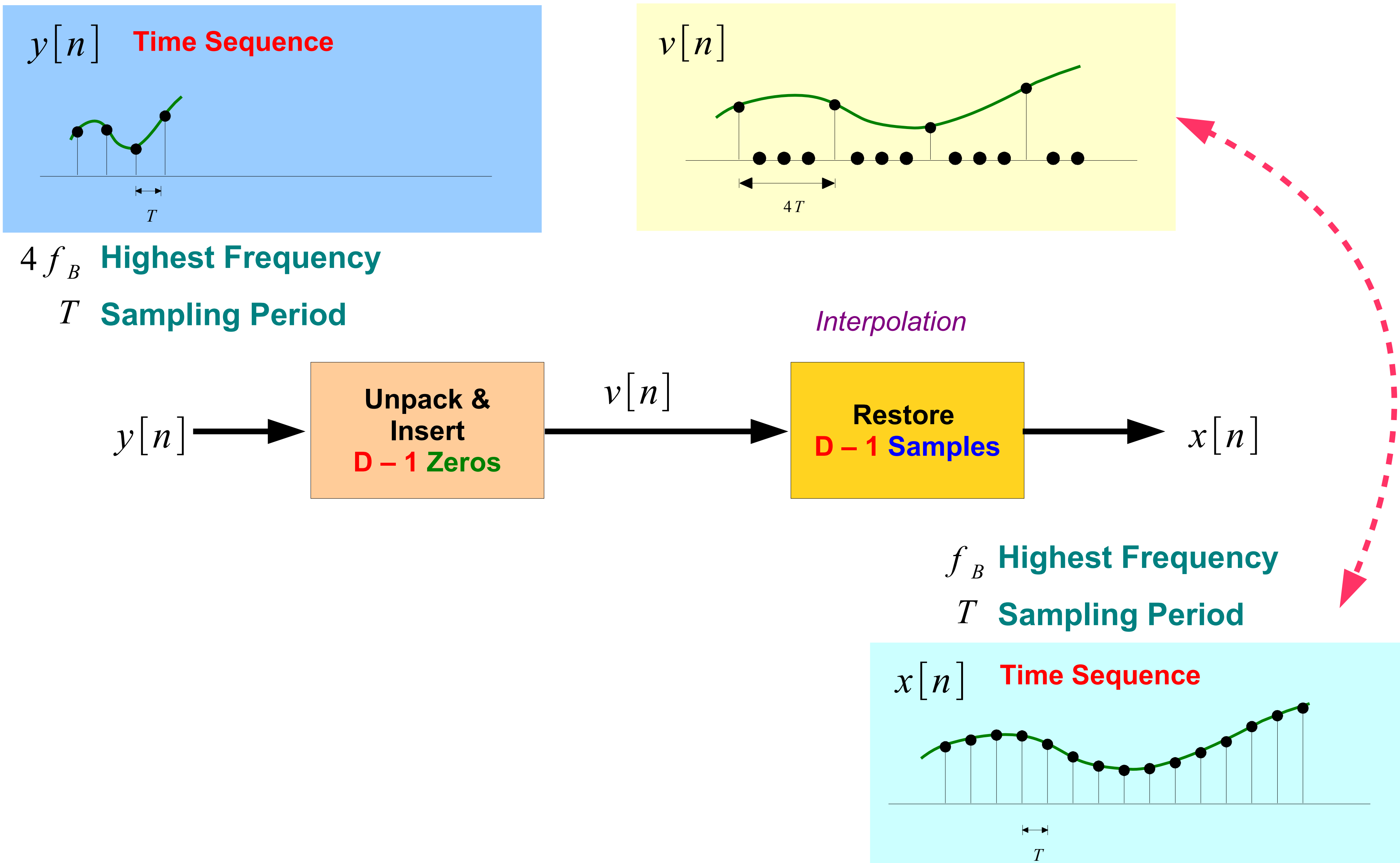
➡ **Compressed**

Normalized Radian Frequency

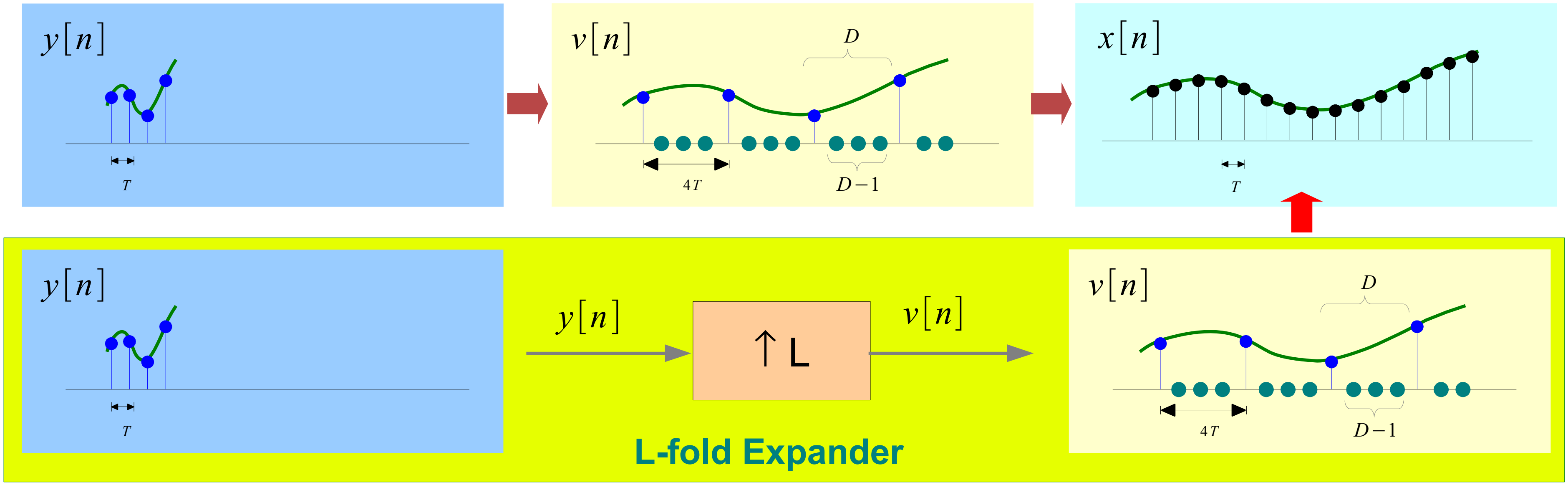
Fine Sequence Generation



Up Sampling in Two Steps



Up-Sampling Operator



$$v[n] = S_L\, y[n] = \begin{cases} y[n/L] & \text{if } \mathbf{mod}(n/L) = 0 \\ 0 & \text{otherwise} \end{cases}$$

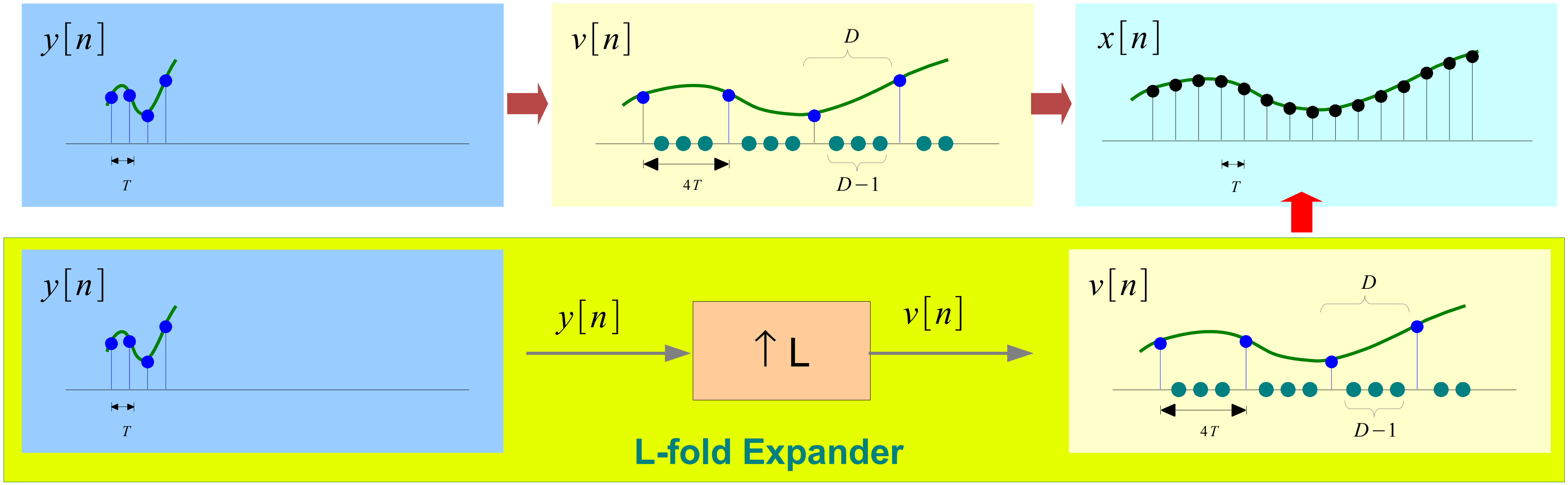
Increase sampling frequency by a factor of L

Decrease sampling period by a factor of 1/L

$D = 2$

$n=0\cdot 2=0$	$v[0] = y[0]$	$v[1] = 0$
$n=1\cdot 2=2$	$v[2] = y[1]$	$v[3] = 0$
$n=2\cdot 2=4$	$v[4] = y[2]$	$v[5] = 0$
$n=3\cdot 2=6$	$v[6] = y[3]$	$v[6] = 0$
	$\cdots$	$\cdots$

Up-Sampling Operator



$v[n] = S_L\, y[n] = \begin{cases} y[n/L] & \text{if } \mathbf{mod}(n / L) = 0 \\ 0 & \text{otherwise} \end{cases}$

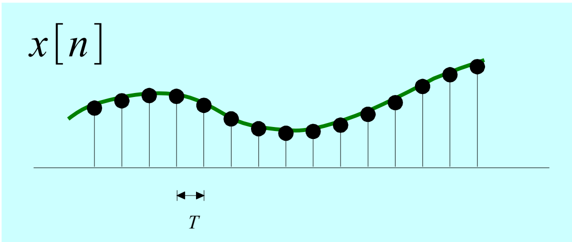
$y[n] = e^{j\hat{\omega} n}$ ⇒ $v[n] = e^{j\hat{\omega} n/D}\, \delta_D[n]$

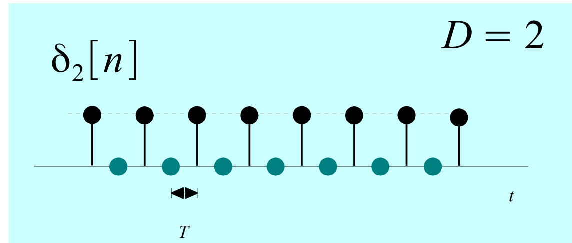
$-\pi \le \hat{\omega} \le +\pi$ $\quad -\pi \le \hat{\omega}/D \le +\pi$ compressed

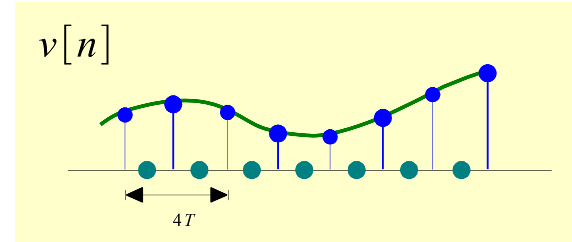
$-D\pi \le \hat{\omega}_1 \le +D\pi$ $\quad -\pi \le \hat{\omega}_1/D \le +\pi$

$\hat{\omega}_2 > +\frac{\pi}{D}$ $\quad \hat{\omega}_2 D > +\pi$

Example When D=2 (1)



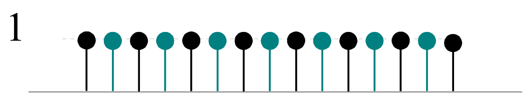


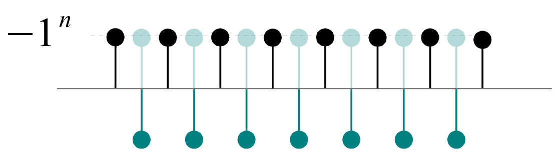


$$x[n] = e^{j\omega n}$$

$$\delta_2[n] = \tfrac{1}{2}\left(1 + (-1)^n\right)$$
$$= \tfrac{1}{2}\left(1 + e^{-j\pi n}\right)$$
$$\left(e^{-j\pi} = -1\right)$$

$$v[n] = \tfrac{1}{2}x[n] + \tfrac{1}{2}e^{-j\pi n}x[n]$$
$$= \tfrac{1}{2}e^{j\omega n} + \tfrac{1}{2}e^{-j\pi n}e^{j\omega n}$$
$$= \tfrac{1}{2}e^{j\omega n} + \tfrac{1}{2}e^{+j(\omega-\pi)n}$$





$$V(z) = \frac{1}{2}\sum_{n=-\infty}^{+\infty}\left(x[n]z^{-n} + x[n](-z)^{-n}\right) = \frac{1}{2}X(z) + \frac{1}{2}X(-z)$$

$$V(e^{j\hat{\omega}}) = \frac{1}{2}X(e^{j\hat{\omega}}) + \frac{1}{2}X(e^{-j\pi}e^{j\hat{\omega}})$$

$$V(\hat{\omega}) = \frac{1}{2}X(\hat{\omega}) + \frac{1}{2}X(\hat{\omega} - \pi)$$

Z-Transform Analysis

$$\delta_D[n] = \begin{cases} 1 & \text{if } n/D \text{ is an integer} \\ 0 & \text{otherwise} \end{cases}$$

$$v[n] = \delta_D[n]x[n]$$

$$V[z] = \cdots + v[0]z^0 + v[D]z^{-D} + v[2D]z^{-2D} + \cdots$$

$y[n]$

$$V[z] = \sum_{n=-\infty}^{+\infty} v[n]z^{-n} = \sum_{m=-\infty}^{+\infty} v[mD]z^{-mD} = F(z^D)$$

T **Sampling Period**

Z-Transform Analysis

$$\delta_2[n] = \frac{1}{2}\left(1 + (-1)^n\right) = \frac{1}{2}\left(1 + e^{-j\pi n}\right) = \begin{cases} 1 & \text{if } n/2 \text{ is an integer (even)} \\ 0 & \text{otherwise} \end{cases}$$

$$e^{-j\pi} = -1$$

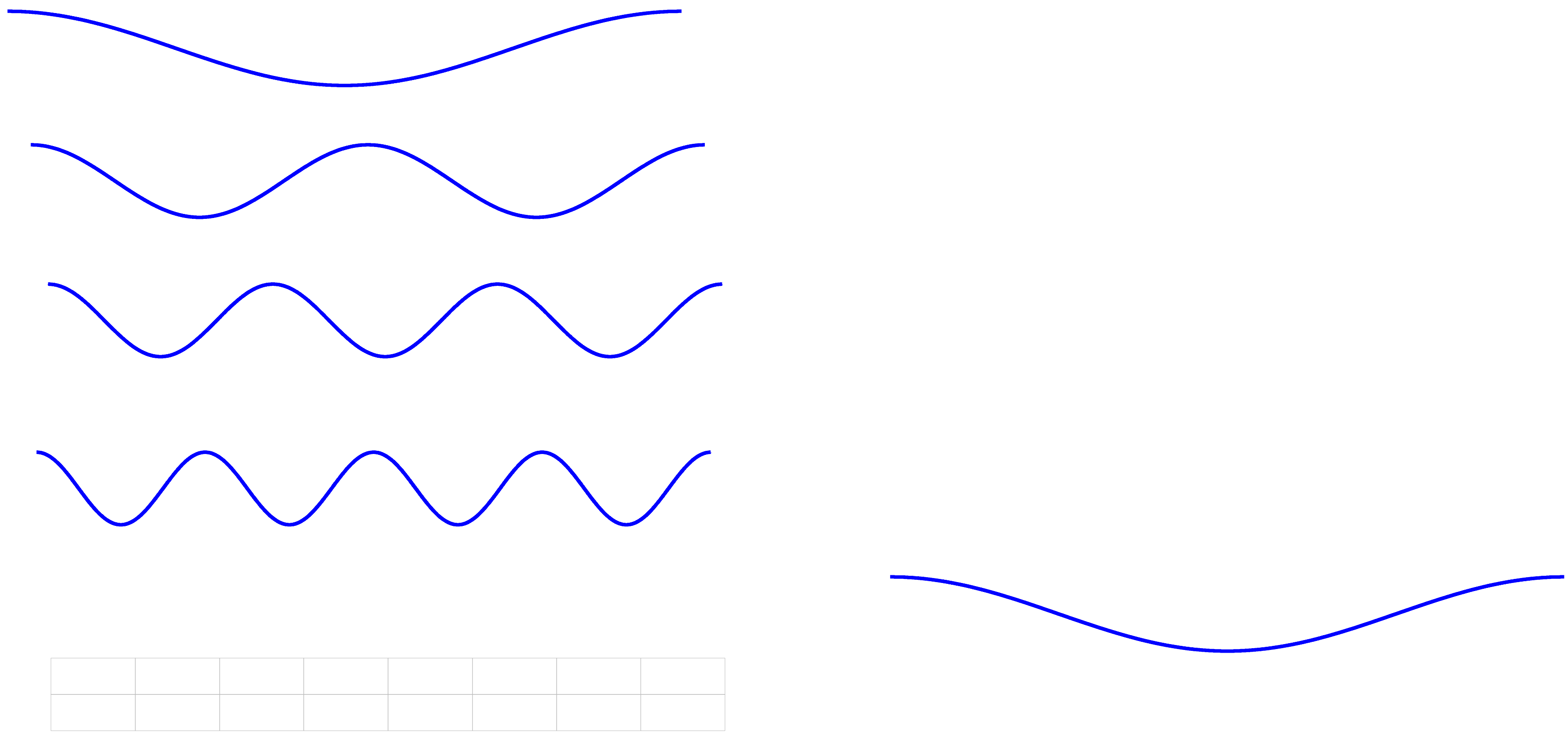
$$v[n] = \frac{1}{2}x[n] + \frac{1}{2}e^{-j\pi n}x[n] \qquad x[n] = e^{j\omega n}$$

$$v[n] = \frac{1}{2}e^{j\omega n} + \frac{1}{2}e^{-j\pi n}e^{j\omega n} = \frac{1}{2}e^{j\omega n} + \frac{1}{2}e^{+j(\omega-\pi)n}$$

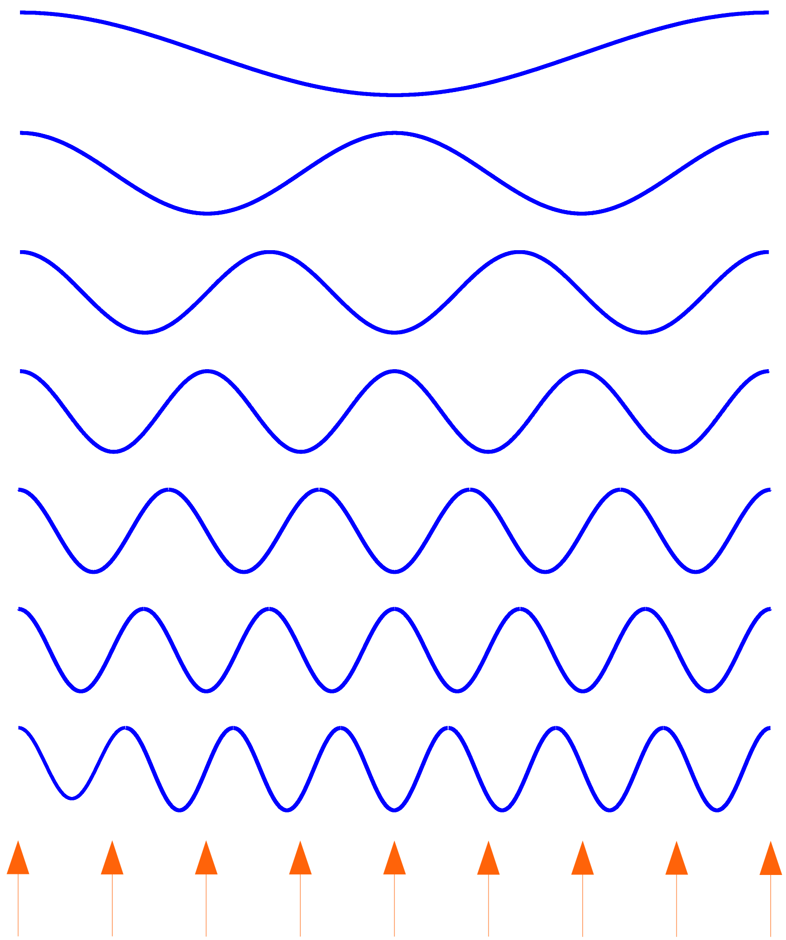
$$V(z) = \frac{1}{2}\sum_{n=-\infty}^{+\infty}\left(x[n]z^{-n} + x[n](-z)^{-n}\right) = \frac{1}{2}X(z) + \frac{1}{2}X(-z)$$

$$V(\omega) = V(e^{j\omega}) = \frac{1}{2}X(e^{j\omega}) + \frac{1}{2}X(e^{-j\pi}e^{j\omega}) = \frac{1}{2}X(\omega) + \frac{1}{2}X(\omega - \pi)$$

Measuring Rotation Rate



Signals with Harmonic Frequencies (1)



1 Hz *1 cycle / sec* $\cos(1 \cdot 2\pi t) = \dfrac{e^{+j(1\cdot 2\pi)t} + e^{-j(1\cdot 2\pi)t}}{2}$

2 Hz *2 cycles / sec* $\cos(2 \cdot 2\pi t) = \dfrac{e^{+j(2\cdot 2\pi)t} + e^{-j(2\cdot 2\pi)t}}{2}$

3 Hz *3 cycles / sec* $\cos(3 \cdot 2\pi t) = \dfrac{e^{+j(3\cdot 2\pi)t} + e^{-j(3\cdot 2\pi)t}}{2}$

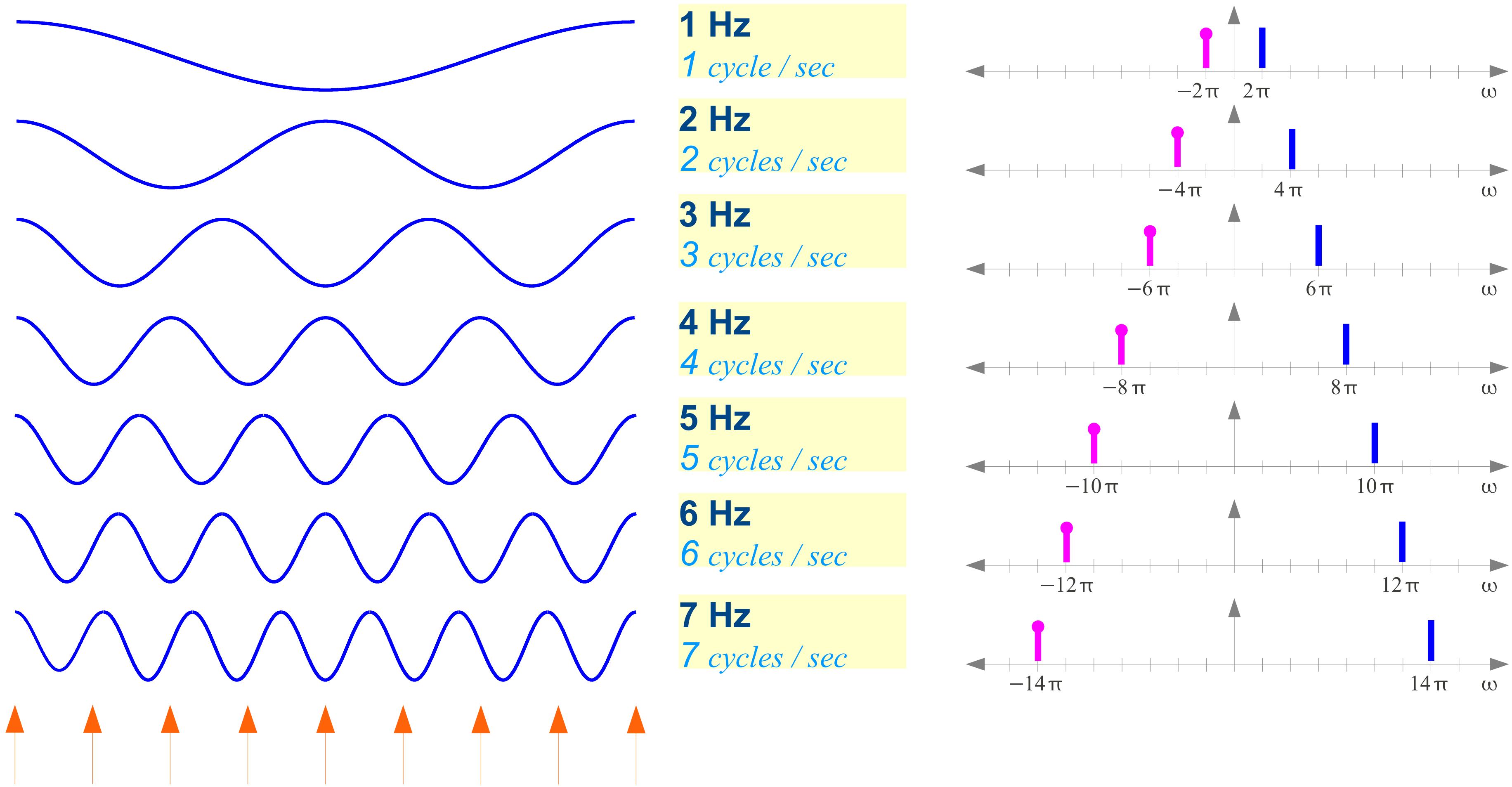
4 Hz *4 cycles / sec* $\cos(4 \cdot 2\pi t) = \dfrac{e^{+j(4\cdot 2\pi)t} + e^{-j(4\cdot 2\pi)t}}{2}$

5 Hz *5 cycles / sec* $\cos(5 \cdot 2\pi t) = \dfrac{e^{+j(5\cdot 2\pi)t} + e^{-j(5\cdot 2\pi)t}}{2}$

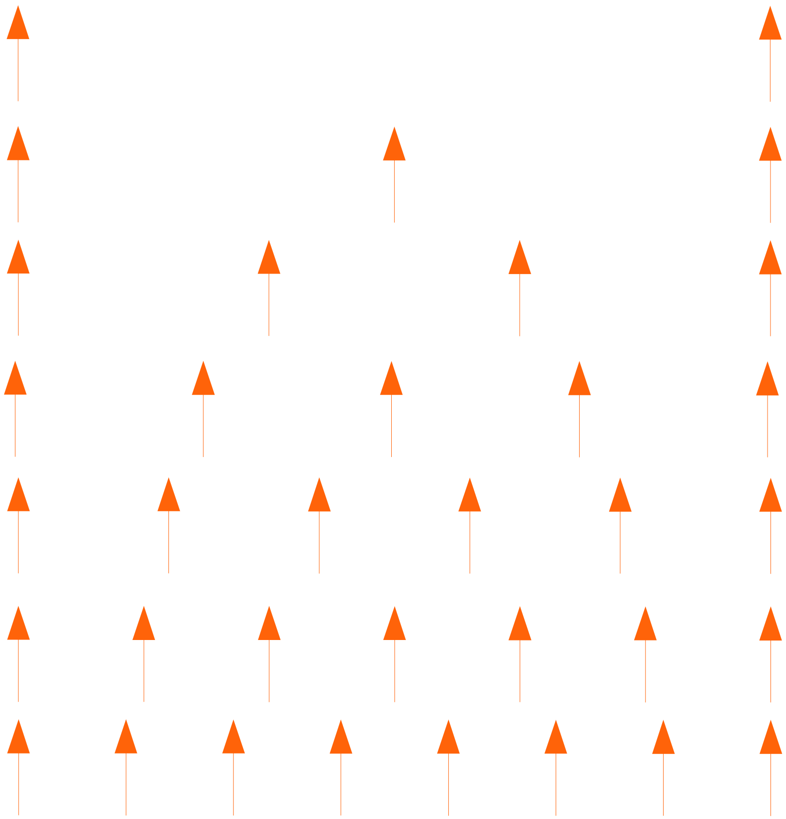
6 Hz *6 cycles / sec* $\cos(6 \cdot 2\pi t) = \dfrac{e^{+j(6\cdot 2\pi)t} + e^{-j(6\cdot 2\pi)t}}{2}$

7 Hz *7 cycles / sec* $\cos(7 \cdot 2\pi t) = \dfrac{e^{+j(7\cdot 2\pi)t} + e^{-j(7\cdot 2\pi)t}}{2}$

Signals with Harmonic Frequencies (2)



Sampling Frequency



1 Hz
1 sample / sec

2 Hz
2 samples / sec

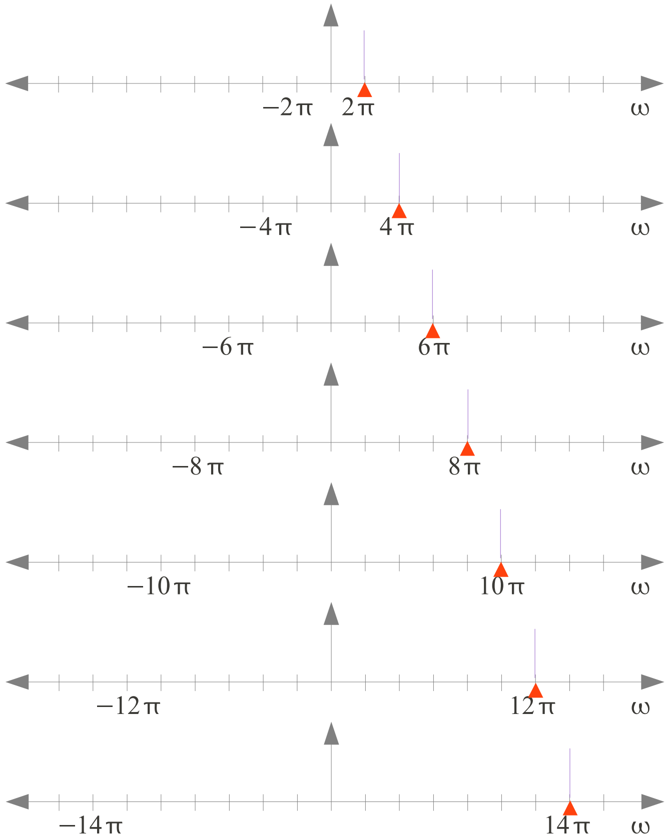
3 Hz
3 samples / sec

4 Hz
4 samples / sec

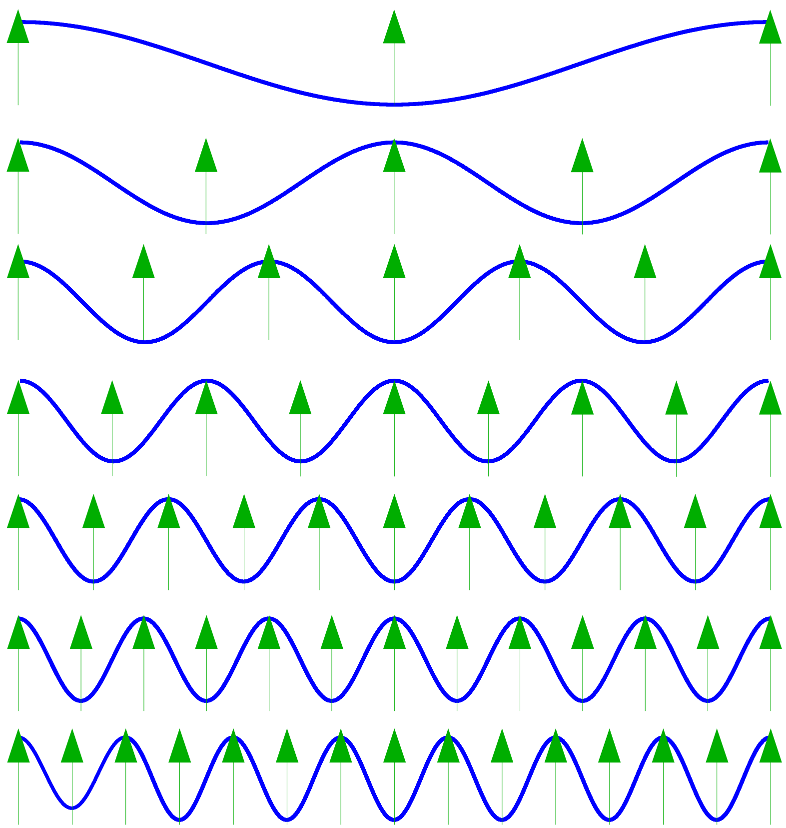
5 Hz
5 samples / sec

6 Hz
6 samples / sec

7 Hz
7 samples / sec



Nyquist Frequency



1 Hz
1 cycle / sec — *2x1 sample / sec*

2 Hz
2 cycles / sec — *2x2 samples / sec*

3 Hz
3 cycles / sec — *2x3 samples / sec*

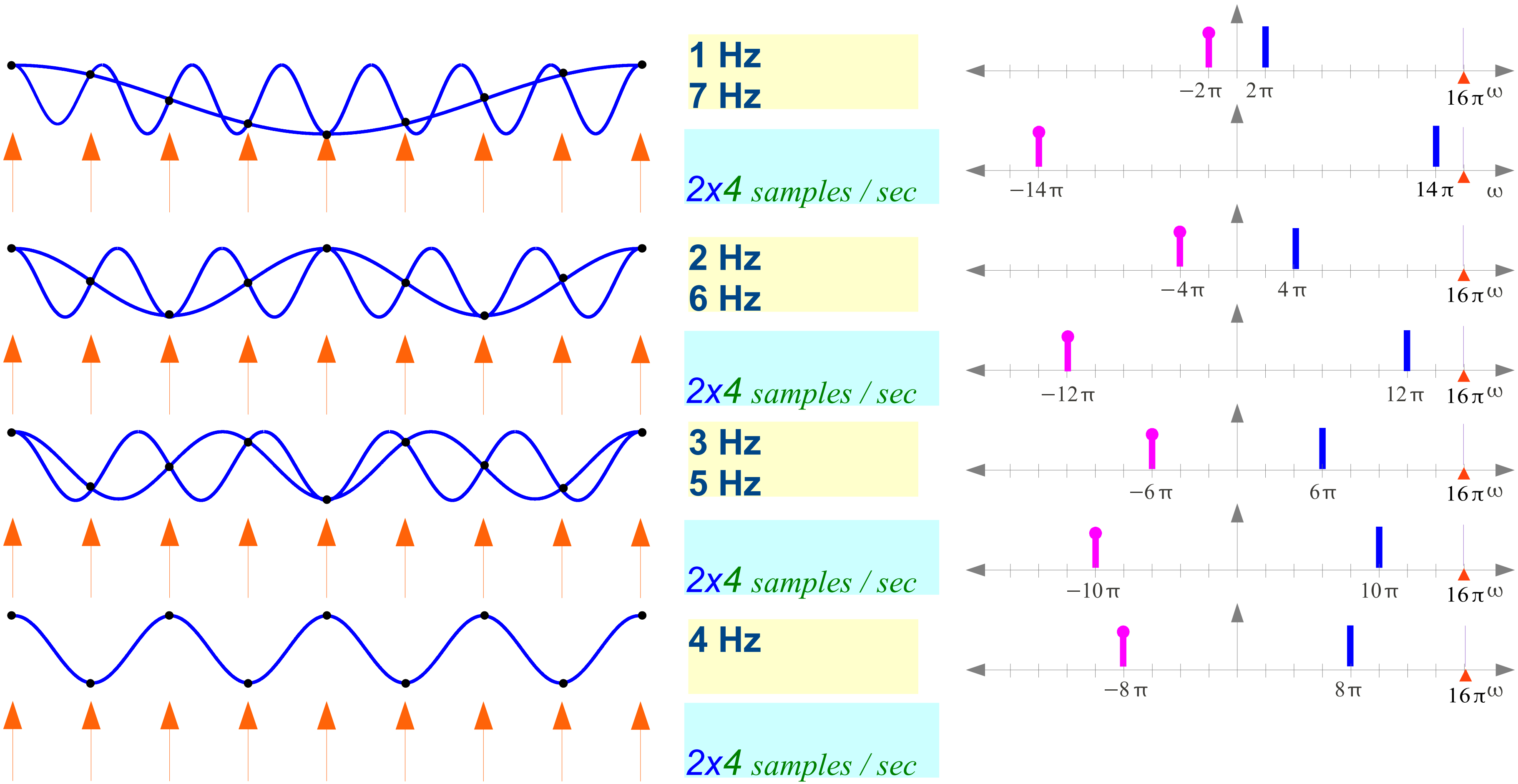
4 Hz
4 cycles / sec — *2x4 samples / sec*

5 Hz
5 cycles / sec — *2x5 samples / sec*

6 Hz
6 cycles / sec — *2x6 samples / sec*

7 Hz
7 cycles / sec — *2x7 samples / sec*

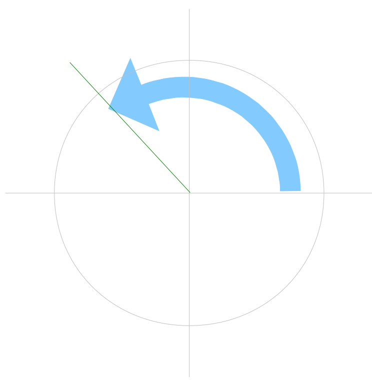
Aliasing



1 Hz
7 Hz
2x4 samples / sec
2 Hz
6 Hz
2x4 samples / sec
3 Hz
5 Hz
2x4 samples / sec
4 Hz
2x4 samples / sec
−2π
2π
16π
ω
−14π
14π
ω
−4π
4π
16π
ω
−12π
12π
16π
ω
−6π
6π
16π
ω
−10π
10π
16π
ω
−8π
8π
16π
ω

Sampling

$$\omega_s = 2\pi f_s \quad (rad/sec)$$



$$\omega_1 = 2\pi f_1$$

$$\omega_1 = \frac{\omega_s}{2} \quad (rad/sec)$$

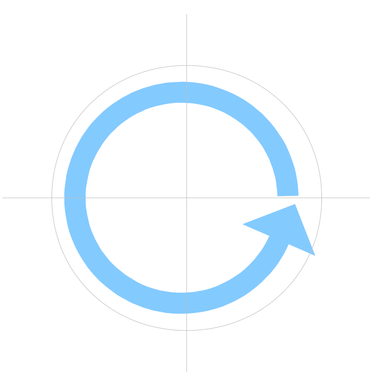
$$f_1 = \frac{f_s}{2} \quad (rad/sec)$$

$$\omega_2 = 2\pi f_2$$

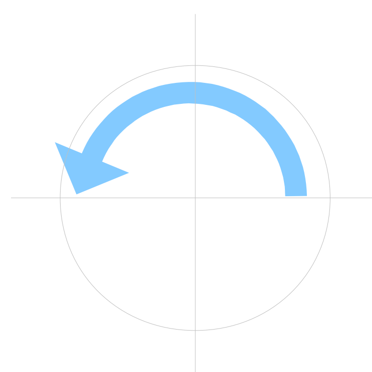
$$\omega_2 = -\frac{\omega_s}{2} \quad (rad/sec)$$

$$f_2 = -\frac{f_s}{2} \quad (rad/sec)$$

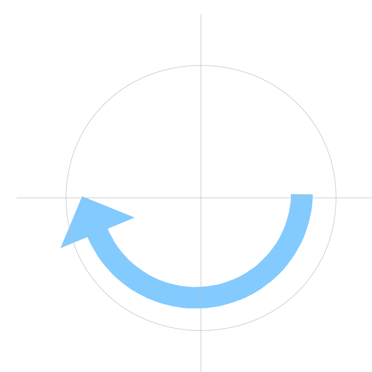
$$2\pi \ (rad) \ / \ T_s \ (sec)$$



$$\pi \ (rad) \ / \ T_s \ (sec)$$

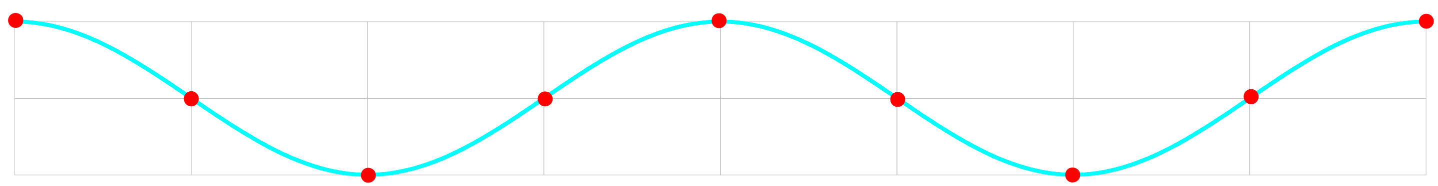


$$-\pi \ (rad) \ / \ T_s \ (sec)$$

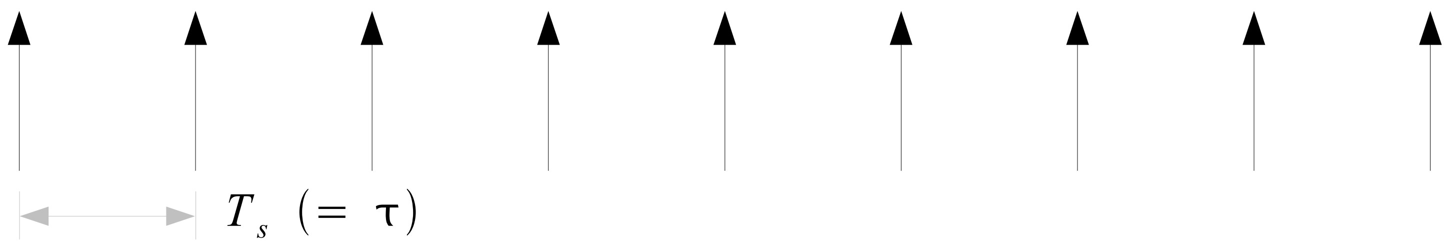


Sampling

$\omega_1 = 2\pi f_1 \ (rad/sec)$

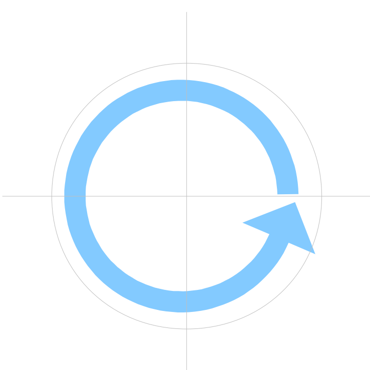


$\omega_s = 2\pi f_s \ (rad/sec)$

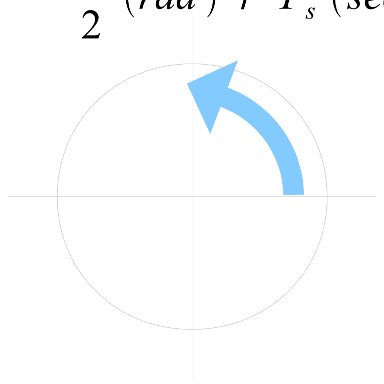


$T_s \ (= \tau)$

$2\pi \ (rad) \ / \ T_s \ (sec)$



$\frac{\pi}{2} \ (rad) \ / \ T_s \ (sec)$



For the period of T_s

Angular displacement $\frac{\pi}{2} \ (rad)$

$$\hat{\omega} = \omega \cdot T_s \ (rad)$$

$$= 2\pi f_1 \cdot T_s \ (rad)$$

$$= 2\pi \frac{f_s}{4} \cdot T_s \ (rad)$$

$$= \frac{\pi}{2} \ (rad)$$

Angular Frequencies in Sampling

continuous-time signals

Signal Frequency

$$f_0 = \frac{1}{T_0}$$

Signal Angular Frequency

$$\omega_0 = 2\pi f_0 \quad (rad/sec)$$

sampling sequence

Sampling Frequency

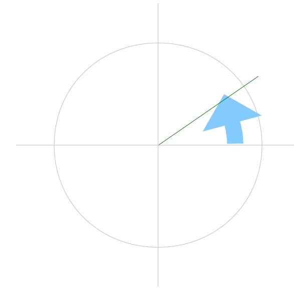
$$f_s = \frac{1}{T_s}$$

Sampling Angular Frequency

$$\omega_s = 2\pi f_s \quad (rad/sec)$$

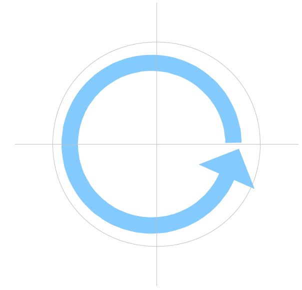
For 1 second

$$\omega_0 = 2\pi f_0 \quad (rad/sec)$$



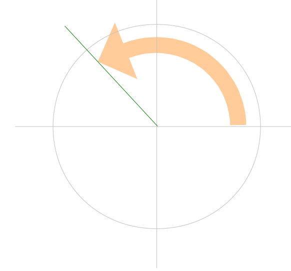
For 1 revolution

$$2\pi\,(rad) \;/\; T_0\,(sec)$$



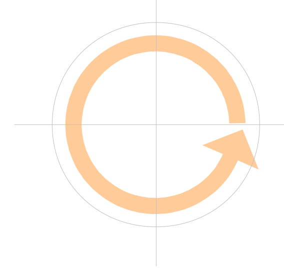
For 1 second

$$\omega_s = 2\pi f_s \quad (rad/sec)$$



For 1 revolution

$$2\pi\,(rad) \;/\; T_s\,(sec)$$



References

[1] http://en.wikipedia.org/
[2] J.H. McClellan, et al., Signal Processing First, Pearson Prentice Hall, 2003
[3] A “graphical interpretation” of the DFT and FFT, by Steve Mann
[4] R. Cristi, “Modern Digital Signal Processing”